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14. ABSTRACT This project has developed new electron diffraction methods for determining the structure of organic sensors and detectors, including a colorimetric diacetylene phospholipid which changes color when exposed to toxins, and a new hard covalent carbonate. We are concerned with radiation-sensitive molecules which cannot be crystallized for analysis by X-ray crystallography, and with new nanostructured organics which do not form large enough single crystals for X-ray analysis. Since the main problem is radiation damage, we have studied this problem in detail. The use of low electron energies to reduce radiation damage has proven effective. We have obtained the first transmission electron diffraction patterns at a beam energy below the carbon K -shell ionization energy (285 eV). We have designed and constructed a field-emission point-projection electron microscope (PPM), a facility for making coated nanotip field emitters, a low energy electron diffraction camera, and facilities for making thin organic films by the Langmuir Blodgett and other methods. The PPM has successfully given nanometer-resolution coherent electron holograms and reconstructed images, at 200 eV, of Tobacco Mosaic Virus. In addition, we have solved a new organic crystal structure whose sub-micron grain-size prevented it being solved by any other method. This material holds promise as a hard, light, optical material. In summary, we now have the hardware and software in place to image useful organic molecules which do not form large enough crystals for conventional analysis.				
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13. ABSTRACT (Maximum 200 words)

This project has developed new electron diffraction methods for determining the structure of organic sensors and detectors, including a colorimetric diacetylene phospholipid which changes color when exposed to toxins, and a new hard covalent carbonate. We are concerned with radiation-sensitive molecules which cannot be crystallized for analysis by X-ray crystallography, and with new nanostructured organics which do not form large enough single crystals for X-ray analysis. Since the main problem is radiation damage, we have studied this problem in detail. The use of low electron energies to reduce radiation damage has proven effective. We have obtained the first transmission electron diffraction patterns at a beam energy below the carbon K -shell ionization energy (285 eV). We have designed and constructed a field-emission point-projection electron microscope (PPM), a facility for making coated nanotip field emitters, a low energy electron diffraction camera, and facilities for making thin organic films by the Langmuir Bludgett and other methods. The PPM has successfully given nanometer-resolution coherent electron holograms and reconstructed images, at 200 eV, of Tobacco Mosaic Virus.

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1. Statement of problem studied.

New Organic materials are finding increasing uses as sensors and detectors with applications for ARO. Many of these bio-molecules cannot be crystallized for study by Xray crystallography. This research aims to develop new methods of imaging organic materials at sub-nanometer resolution in order to understand and improve their function. An example is the organic molecule DC8,9PC, a diacetylene phospholipid, which changes color when exposed to certain toxins. We have solved this structure by electron diffraction. The material is also used as a high resolution photoresist for nano-lithography.

2. Summary of most important results.

A. A new type of electron microscope has been designed and constructed, which, by operating at very low energy (down to 10 eV) avoids the inner-shell ionization processes which cause most radiation damage to biomolecules. This point-projection field-emission instrument forms coherent in-line Gabor holograms of molecules at about 1nm resolution. Methods for forming the required nanotip field-emitters have successfully been developed. We have used this instrument to successfully record holograms from Tobacco-Mosaic Virus, Purple Membrane (responsible for photosynthesis) and Copper Thalocyanine, and we have reconstructed images from these holograms. New methods of solving the twin-image problem of in-line holography have also been developed. The effects of coating field-emission tips to reduce work function has been studied experimentally. Extensive theoretical work has been done on the problem of extracting structural information with least damage when imaging biomolecules (see refs. below).

B. Damage Thresholds. By measuring the time in seconds it takes Bragg spots to fade out (due to radiation damage) as a function of beam energy in the TEM, we have shown that threshold energies exist. These threshold energies correspond to the main ionization energies of the atoms in the sample. Spots take much longer to fade if the beam energy is less than these threshold energies (eg at 285 eV for the carbon K shell excitation), suggesting ways to determine molecular structure with less damage. Experimentally we have obtained the first ever transmission electron diffraction patterns at energies below the carbon K ionization energy. At very low energies, the range of elastically scattered electrons increases with decreasing energy, and we have reported transmission experiments in this range.

C. Solving organic structures by Transmission Electron Diffraction (TED). We have now solved two important crystal structures by TED. The first is the colorimetric DC8,9PC, a diacetylene phospholipid, which changes color when exposed to certain toxins. Our original aim was to solve this structure with, and without, the toxin attached, in order to understand how it binds. To do this we have used the Direct Methods numerical techniques of X-ray crystallography in order to solve the phase problem of TED. These lipids are light-element thin films of known thickness (two molecular layers thick), highly suitable for this work. The use of the elastic, imaging energy -filter on our Leo 912 Omega electron microscope was crucial to this work. The second structure solved was a new light element carbonate synthesised at ASU Chemistry, consisting of a continuously bonded covalent organic crystal. This work has been submitted for publication. **The significance of this work is that our TED method can deal with the sub-micron crystallite sizes found in many of the new nano-structured materials** , which, especially if radiation sensitive, cannot be solved by conventional methods. Our method combines NMR results with TED and Direct Methods software.

3. Listing of publications.

- 158 Radiation damage and point projection imaging of biomolecules at very low voltage. J. Spence. J.Electr.Micros. 30, p. 215 (1996) . (In Japanese) ARO DAAH04-96-1-0231.
- 167 "STEM and shadow imaging of biomolecules at 6 eV beam energy". J.C.H.Spence. Micron 28, p. 101-116. (M. J. Whelan Festschrift) 1997. .ARO
- 179 "Reflection shadow imaging of crystal surface by low-voltage point-reflection microscopy Xu Zhang , Uwe Weierstall, John C. H. Spence. Ultramic. 72, p. 67-81. 1998. ARO DAAH04-96-1-0231.
- 180 "Is molecular imaging possible ?" J. Spence. Chapter in "Topics in electron diffraction and microscopy of materials" . P.B. Hirsch Ed. (Festschrift for Prof M. J. Whelan). 1999. I.O.P. London. ISBN 075030538 ARO DAAH04-96-1-0231.

187 "Imaging of Tobacco Mosaic Virus at 40 volts by electron holography". U. Weierstall and J. Spence. Proc. Int. Congr. Electr. Micros. (Cancun) 1998. ARO DAAH04-96-1-0231

193 "Point-projection electron imaging of TMV at 40eV electron energy". U. Weierstall, J.C.H. Spence, M. Steve K.H. Downing. *Micron* 30(4) p.335-338 (1999). ARO DAAH04-96-1-0231.

194 "Wavefront reconstruction for in-line holograms formed by pure amplitude objects". X. Huang, J.M. Zuo and J.C.H. Spence. *Applied Surf. Sci.* 148, 229-234 (1999). ARO DAAH04-96-1-0231.

206 "Transmission electron diffraction at 200 eV and damage-thresholds below the carbon-K edge. M.R. Stevens, Q. Chen, U. Weierstall and J. Spence. *Micron and Microan.* 6, p. 368 (2000) (Festschrift for A. Howie). ARO DAAH04-96-1-0231.

214 "Image reconstruction from TEM diffraction patterns using Feinup algorithm. Q. Chen, U. Weierstall, J. Spence. *Proc. MSA.* 2000. In press. ARO.

215 Investigation of polymerized phospholipid monolayer thin film structures by energy-filtered transmission electron diffraction. M. Stevens, M.L. Longo and J. Spence. *Proc MSA.* (G.W. Bailey, Ed. Springer) 2000. p. 1130. ARO.

211 "A modern approach to x-ray holography". M. Howells, B. Calef, C. Jacobsen, J. Spence, and W. Yun. in *Proc. X- Ray Microscopy 1999.* AIP Conference Proceedings. American Institute of Physics.

212 "Hard X-ray Microscopy and Tomography at the ALS. W. Yun, M. Howells, J. Feng, R. Celestree, C. Chang, A. MacDowell, H. Padmore, J. Spence. *Proc VIIth Int Conf on X-ray Microscopy*" 1999. AIP Conference Proceedings. American Inst. of Physics. p 8-14

220 "Structure analysis of polymerized phospholipid bilayer by TED and Direct Methods. M. Stevens, M. Longo, D. Dorset, J. Spence. *Ultramic.* In press ARO DAAH049610231.

221 "Image reconstruction from electron and X-ray diffraction patterns using iterative algorithms: experiments and simulations". U. Weierstall, Q. Chen, J. Spence, M. Howells and R. Panepucci. *Ultramic.* In press 2001. ARO DAAH049610231.

229 "Toward a practical X-ray Fourier Transform holography at high resolution". M.R. Howells, C. Jacobsen, S. Marchesini, S. Miller, J. Spence, U. Weierstall. *Nucl Instr. Methods.* (Proc XRM 2000).

Several technical and interim reports have already been submitted to ARO under this award. The PhD Thesis of Dr. M. Stevens and the MSc thesis of X. Huang will be forwarded to ARO. Reprints of papers will be forwarded shortly.

4. Listing of personnel.

1. Prof J. Spence. P.I.
2. Dr. U. Weierstall. Academic Professional, supported by ASU.
3. Dr. Q. Chen. Post Doc. Supported by this award.
4. Mr. X. Huang. Supported by this award. M. Sc in Physics obtained in 1998.
5. Dr. M. Stevens. Physics PhD student supported by this award. PhD awarded 2001.
6. Several other collaborators listed in references above at other institutions, not supported by this award.

5. Report of inventions.

None.

6. Bibliography.

See reference list above.

